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Simulation of solar heating systems—an overview

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Abstract

Process simulation has become an accepted tool for the performance, design, and optimization of thermal processes. Solving the mathematical models representing solar heating process units and systems is one of the most tedious and repetitive problems. Nested iterative procedures are usually needed to solve these models. To tackle these problems, several researchers have developed different methods, techniques, and computer programs for the simulation of very wide verity of solar heating process units and systems.

It is of interest in this work to characterize and classify these methods, techniques, and programs in order to better understand their relations, types, structures, and procedures.

The simulation problems are outlined; the simulation programs are grouped into two main types; special purpose, and general-purpose programs. Sequential and simultaneous computational sequences are illustrated. Simulator structure, program evaluation, and numerical techniques are summarized.

By considering the unit and/or system entropy generation as well as the energy and material balances equations, more realistic models can be obtained. Also, rapid development of computer hardware and software will suggest new techniques and programs to be considered. These progress directions are noted.

Keywords: Simulation; Solar heating systems; Program types; Computational sequence; Simulator structure

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Contents

1. Introduction

The demand for efficient solar heating processes requires suitable computational tools for designing and evaluating new and existing processes. Process simulator (also called process flow sheeting) has become an accepted tool for this purpose. Also, it is currently used in both industry and engineering education. Any attempt to gain information about a process by carrying out calculations on a mathematical model of that process is defined as a simulation [1,2].

The mathematical model representing material and energy balance of a solar heating process may comprise a large system of equations characterized by complexity, non-linearity, and implicitly. The nested and countercurrent information flow nature of the problem adds to the difficulty of the solution of such process. With a flexible computer program, a large number of flow sheeting problems can be tackled. These problems can be generally divided into three classes: (i) performance problems, (ii) design problems, and (iii) optimization problems.

Many ‘special’ computer programs designed for different solar heating system calculations have been reported [3]. However, when only ‘general’ programs are considered, i.e. programs not restricted to a certain type of calculations, to a fixed flow sheet, certain physical data, only a few programs can be found in the literature [4].

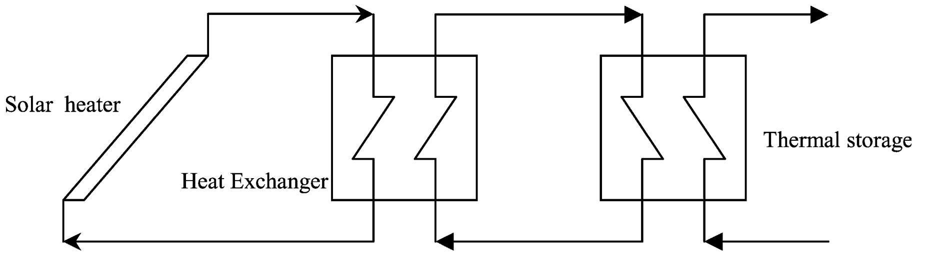

Fig. 1. Solar heating process.

Without properly classified programs, methods, techniques, and problems, one cannot hope to make headway in the field of solar heating process simulation. In fact, no such classification is available in the open literature for this subject.

The main purpose of this article is to present an overview of the main lines of the design and modeling philosophy utilized in developing solar heating process simulation programs. A classification of the concepts, programs, and techniques of a large number of available mathematical models for these processes are also outlined. Of course, because of the space and time limitations the paper cannot go in details.

2. Simulation problems

Consider a typical solar heating process, as shown in Fig. 1, and suppose that one wants to simulate its performance. The first step in the modeling of the process is to structure it. This leads to a flow sheet of coupled blocks that can be modeled independently, Fig. 2. Each of lettered blocks represents a processing unit. Each of these units is connected to at least one of the other units by one or more pipes or streams as indicated by the numbered line. Arrows into a box indicate streams that must be known in order to simulate that unit. Arrows out of the box indicate streams, which are computed from the process simulation mathematical model

Once it has been decided which streams are inputs to each unit and which are outputs, some connection equations between the two must be determined as; output variables $=F$ (input variables). This model equation of the individual units is, of course, the most important aspect of process simulation. Generally, the input variables are the inlet feed stream variables and the model parameters. The output variables are the outlet stream

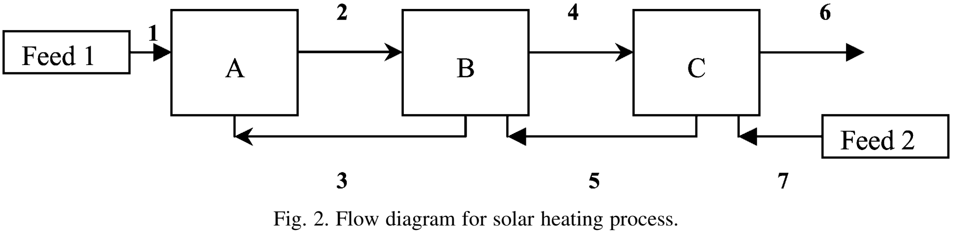

Fig. 2. Flow diagram for solar heating process.

variables, performance and sizing results. Also, the various physical parameters such as transfer area, transfer coefficient, etc. are contained in the model equations.

Now, if the process flow diagram is without recycle streams and the feed streams are known, it is then possible to calculate the whole process by working through the units sequentially. This is the most straightforward form of the simulation problem. However, if the process does have one or more recycle streams as input, one must make initial estimations of all these recycle streams. This leads to a set of computed values for each of the recycle streams that are then compared with the original estimations. Some iterative procedure is then used to continue calculations around the units (in the recycle loop) until the streams match each other.

Iterations may exist at several levels, for instance, stream 2 depends not only on the value of stream 1, but it also depends on the value of stream 3. Nevertheless, if we tear (break) streams 3 and 5 then use an iterative procedure until the values of torn variables are equal to the values obtained by the calculation, then the value of stream 6 (product) is obtained. Another level of iteration may arise because of the complexity of the mathematical models used to describe the process units. For example, if the heat storage tank (unit C) is modeled by a non-linear mathematical model. This model will be solved iteratively to calculate streams 5 and 6 form streams 4 and 7. Finally, the third level of iteration may arise if one wants to calculate the feed (stream 1) in order to obtain a product of given specification (stream 6). This requires iteration on the values of streams 2–5, and 7 until stream 6 has the specified values. So, it is quite clear why simulation is a real problem. Several types of problems can be solved by a simulation program (flow sheeting program) [5].

In the *performance problem*, the variables associated with the feed streams to a process unit and all design parameters (such as solar collector area, heat exchanger area, etc.) are assumed to be known. The variables associated the internal and output streams are the unknowns.

In the *design problem*, some design parameters and/or feed variables are left unspecified and become unknown. A corresponding number of additional equations (equality constraints) relating some of these variables are added, such that the total number of unknowns equates the number of equations.

The *optimization problem* differs from the design problem in that the number of equality constraints is smaller than that of the variables left unspecified. The unspecified variables are now calculated so as to minimize an objective function, normally of economic nature. In this case, the solution can be considered also by using inequality constraints.

3. Simulation programs

Many computer programs for different solar heating processes have been reported in the literature [3,4]. These programs can be grouped into two main types: special purpose programs, and general-purpose programs.

3.1. Special purpose programs (one-off programs)

For a particular solar heating process (or unit) with a fixed configuration, it is possible to write a mathematical model describing that process is in the form of a 'one-off' computer program. The structure of these programs is rigid, simple, and straightforward. All that the user has to supply, is the data and the executive handles the program in the same way, irrespective of the nature of the process simulated.

The disadvantage of such programs is that a model exists for only one process and any changes made to that process might require extensive re-programming. However, the specialized program makes it much easier to produce mathematical models of sufficient realism. Also, when writing general-purpose models of a standard unit operations, often a great deal of time is spent preserving a degree of generality and reliability in performance which may not be relevant to a particular problems [6]. This type of programs utilizes two different computational sequences.

3.1.1. Sequential marching technique

In this approach, each model equation is handled in an order that allows it to calculate sequentially the unknown variables. Using this technique, the mathematical model equations representing heat pump system with refrigerant-filled collectors in space heating applications was solved by O'Dell et al. [7]. The system consists of conventional air source, heat pumps, and active liquid solar collector units. Equations representing these units are solved sequentially. An analytical model for a self-pumping, boiling collector system was developed and incorporated into a daily simulation by Walker and Davidson [8]. The model simulates system operation in three distinct isothermal passes: pressurizing, pumping, and running (heating). The conservation of mass and energy equations for each model are combined and solved sequentially and iteratively. A new inexpensive type of solar pond, mainly for space heating was proposed by Sokolov and Arbel [9]. The system was divided into four major components: collector, storage, ground and climatic (radiation and temperature) conditions. These unit mode equations are solved sequentially for predicting their system performance. El-Nashar [10] has described the mathematical model used to simulate the operational performance of solar desalination plant which utilizes evacuated tube, flat-plate collectors, and multi-effect stack type evaporators, and thermally stratified heat storage tank. The major components of the process are modeled and solved iteratively in a sequence way. An algorithm based on daily hours of bright sunshine was developed by Nguyen and Galanis [11] The equations representing this algorithm were solved sequentially to evaluate the performance of active solar heating systems for different values of system parameters (collector area and efficiency curves, orientation and inclination, storage capacity, heating load). SOLAV program for numerical calculation of a solar heating system for an individual building was described by Shafeev [12]. SOLAV is one-off program. It consists of three basic programs for generation of climatic actions analysis of the solar heating system, with subprograms for individual components of the solar heating systems and determination of the building's heat demand. AIRSYS computer program was also suggested by Shafeev [13] for designing active air systems of solar heat supply for individual building. The program was used for investigation and preliminary estimation of the heat and energy parameters of

such process. Equations representing a thermosyphanic solar energy water heater, the heat transfer fluid circulates from the solar energy collector to hot water store due to the action of buoyancy forces, are solved sequentially by Norton and Probert [14]. A methodology for the constriction of a mathematical model of a forced convection solar cabinet dryer was demonstrated by Chirarattananon et al. [15]. The dryer was divided into three control volumes. Each control volume model comprises only the variables directly involved in the energy and mass balance relationships. These mode equations are solved sequentially for the state variables of the control volumes. The concept of a portable solar oven using a vapor-tight pot was introduced and theoretically investigated by Ibrahim and Khalifa [16]. The mathematical model involved uses the lumped analysis approach where the whole system is broken up into several elements, each of which is treated as a lumped system by itself. The governing equations of these elements resulting from the heat balance equations are solved on the computer using the fourth-order Runge–Kutta method. A general design procedure for solar-assisted series heat pump systems used for space and process water heating was presented by Svard et al. [17]. Equations representing the process units are solved sequentially. An algorithm to evaluate the performance of the water-cooled pump for any location, given the lift and collector area was presented by Sudhakar et al. [18]. The computer program TRNSYS [4] was used by Jesch and Braun [19] to simulate the performance of both the fixed and variable volume thermal storages. Two differential equations describing the rate of change of mass and internal energy were given. These two simultaneous differential equations were solved for each simulation time step. A detailed computer simulation model of an ammonia–water absorption cycle solar heat pump with integral refrigerant storage was reported by Kaushik et al. [20]. A computer model based on the usual heat and mass balances for different units in the system was developed. The unit models are solved in sequence using one-off program.

Elsayed et al. [3] present a textbook for design and simulation of solar thermal systems using mathematical modeling. Large number of solar heating systems was considered in this book. Mathematical equations to predict the radiation properties of multi-layer partially transparent sheets with or without an absorber plate are given. A program to calculate the radiation properties for several geometries of a stack of similar or non-similar transparent sheets with or without an absorber plate at any incidence angle was given. This program can also perform design and optimization of flat-plate collectors and solar concentrators. A computer program was written by Elsayed et al. to design and optimize the design parameters of the flat collectors, and to calculate various factors affecting their performance. A computer program to design and optimize the design parameters of the flat-plate collectors was illustrated. A computer program was given to assist the designer in predicting the effect of various designs and operating conditions on the performance of different solar desalination systems. The analysis of both the single effect and the multi-effect were presented. Mathematical simulations of various types of sensible heat storage were carried out for low-, intermediate-, and high-temperature applications. In particular, mathematical simulations are presented for the transient performance of the mixed liquid storage, underground liquid storage, and stratified liquid storage. A computer program was also presented to predict the performance of the absorption-cooling machine. Mathematical model was given for a Rankin cycle selection of the various design parameters. The performance of the solar-operated Rankin cycle in various operating

conditions was considered. Analysis is also presented to select the optimum collector temperature for solar-operated power cycles. A solar thermal desalination system with heat recovery was recently modeled by Klemens et al. [21]. Numerical simulation results for the process were obtained by solving energy and mass balance equations for each unit sequentially. The system units are a solar collector and desalination tower. The modeling and simulation of a solar water heating system using time marching model was presented by Bojic et al. [22]. The solar water heater consists of a flat-plate solar collector, a water storage tank, an electric heater, and a water-mixing device. A mathematical model of a solar desalination unit with humidification and dehumidification processes was presented by Dai et al. [23] and Nafey et al. [24]. Different mathematical models were proposed to describe the simultaneous heat and mass transfer process inside solar stills [25]. The process governing equations, including mass, momentum, and energy conversations were solved sequentially using one-off program.

3.1.2. Simultaneous marching technique

In this approach, the considered processing unit or the entire process is mathematically modeled in terms of independent and dependent variables. Then after specifications of the independent variables, one set of simultaneous equations is obtained [6,26,27]. This system of equations is then solved by one of the well-known numerical methods for solution of systems of linear and non-linear equations [28,29], to obtain the process simulation. Using this technique, a space solar water heating system was solved by Dakhoul et al. [30]. The system consists of four units, a collector, heat exchanger, storage tank, and the load area. A set of four non-linear algebraic equations in four unknown temperatures was obtained. This set was simultaneously solved by Newton's iterative method. Adhikari et al. [31] have presented a computer simulation model for studying the steady state performance of a multi-stage stacked tray solar still. The energy balance equations for various components of the system were considered. A set of simultaneous linear equations was obtained for water temperatures in various trays. This set of equations was cast in a matrix form and solved iteratively. A simplified simulation method for solar thermosyphon collectors was developed by Huang and Hsieh [32]. The process was divided into four parts: absorber, storage tank, riser, and down comer. A set of mass and energy balance equations for these subsystems were simultaneously solved by computer to give temperature distribution and flow rate. The heat transfer analysis of an overlapped glass plate air heater unit was presented by Selcuk [33]. Steady and unsteady state performances were considered. Eight simultaneous differential equations were manipulated by finite difference technique, and in a matrix form. A multiple layer solar collector was proposed by Kenna [34]. This process was modeled by a number of differential equations. These equations were linearized and solved iteratively. The model was used to identify the most important design parameters of this collector and compare its performance with flat-plate collector characteristics. A phase change and sensible heat storage was modeled by Ghoneim [35]. Enthalpy equations for a specified element, as well as the energy balance equation for the fluid element were solved iteratively by Gauss–Seidal method. A mathematical model derived from the basic laws governing thermal energy exchange between surfaces was presented by Zhao et al. [36] for the transient simulation of flat-plate collectors. A computer program was coded in BASIC for

the developed model. The concept of subdivisions was introduced in the development of the governing equations for an air type solar collector. Each sub region set of simultaneous equations was solved by Gaussian elimination method. The subsequent subdivision models are solved iteratively in sequence. Choudhury and Garg [37] have developed a mathematical model for jet plate air heater unit. A set of energy balance equations for the cover, absorber, jet plate, back plate, air in the passage between back plate and air between absorber and back plate was solved iteratively for outlet temperature. Using a program specifically written for a storage tank simulation, the finite difference technique was used by El-Nashar and Qambiyeh [38]. A computer simulation of a regenerating-type solar collector using simultaneous approach was presented by Johannsen [39]. The collector was used for the regeneration of a liquid desiccant and forms part of an open-cycle solar air-conditioning system. Heat and mass balance equations for the process components form a set of 13 equations for 13 unknowns. A numerical model for a single stage humidification–dehumidification solar desalination process was presented by Fath and Ghazy [40]. The desalination process consists of a solar air heater, humidifier, dehumidifier and air-driving component (fan). The energy balance equations for the process units were coded by an one-off program and solved simultaneously. Modeling and performance analysis of a single basin solar still with the entering brine flowing between a double glass glazing were investigated by Mousa et al. [41]. A set of non-linear ordinary differential equations representing the process is solved numerically with an adjustable time step procedure. An innovated water desalination system using low-grade solar heat was studied recently by Al-Kharabsheh and Yogi [42]. The system performance was simulated by solving mass, energy, and salt balance equations simultaneously.

3.2. General-purpose programs (modular programs)

Analysis of a number of projects have indicated that the savings which result from the choice of an optimal process configuration are far greater than those resulting form detailed optimization of the operating conditions of a plant of non-optimal layout [43]. The choice of the optimal configuration will involve optimization of each of the alternatives. This would be accomplished usually by means of multiple case studies, which can be easily performed by a flexible general-purpose program. In other word, in order that the computer program can be applied widely for different solar heating processes, with different configurations and different operating conditions it must be flexible and general. To meet these requirements, the modular structure should be adopted [44].

In this structure the mathematical model is usually formulated in terms of sets of equations relating to the units of the process. Each of these sets of equations may be regarded as an independent and self-standing module. This is the basis of the modular flow sheeting approach. Once a module has been developed, it can be used in any number of processes requiring such a module. Modules represent a set of ‘building blocks’ which are selected and assembled by the user to produce a model of the complete process he wishes to study. The flow sheeting approach had been used in the design of chemical processes for a long time. Similar approach was in fact used in other fields, such as electrical engineering, thermal design systems, but these were referred to by other names. Excellent reviews of the early approaches to flow sheeting were given by Westerberg et al. [45]

and Wells and Robson [46]. Flow sheeting programs have manipulated two computational sequences.

3.2.1. Sequential modular approach

In the sequential modular approach, the model equations are handled using a library of ‘modules’ or subroutines. These modules are able to compute output streams for given input streams for each equipment in the simulated process. There is then an executive, which uses the process flow structure to link the subroutines in order to perform the required computation for the whole process. Specification such as input stream data and equipment parameters are easily handled by passing the specified values directly to the proper unit modules. However, other specifications, on output streams for instance, may not accept the specifications. Other specifications that cannot be input directly to a module are referred to as design specifications.

SYSOPT modular program was described by Young [47]. This program uses linear programming technique to optimize the subsystem sizing, performance, and economics of integrated energy systems. The program modular stricture permits the designer to readily interconnect solar subsystem models into alternative configurations of combined solar and conventional technologies. Based on these interconnections and specifications, the program formulates hourly energy/mass flow balances at interconnection points and optimizes both sizing and time-dependent dispatch of the various subsystems. The calling of the available subsystem modules in the optimization program SYSOPT includes solar flat-plate collectors, photovoltaic collectors, wind energy systems, electric storage, thermal storage, turbine generators, power conditioners and inverters, resistance heating, thermal and electric load modules, fossil boiler, diesel generators, utility grid backup and feedback and various process modules such as water desalination. Additional subsystems models can be readily formulated within the overall modular structure. Each subsystem modules is specified by a single subroutine, which returns the appropriate coefficients for each subsystem variable.

TRNSYS (Transient Simulation Program) is a thermal process simulation program. A list of different components in the program library was presented by Duffie and Beckman [4]. The unit mathematical model was represented by a number of algebraic and/or differential equations. Three different integration techniques were used by TRNSYS program. A number of simulation studies for different solar heating processes were reported by Duffie. Duffie hinted five modular computer programs. These are: WATSUN program, which was developed at the university of Waterloo in Canada. This program can manipulate a large number of unit modules. MINSUN program is specifically designed for simulation of systems with seasonal storage where daily temperature changes are small; one-day time step are used. G3 is a simplified program. It is based on daily input–output diagrams. This program is designed for fast and simple evaluation of active systems. ISFH is a versatile program. It includes a means of generating a ‘synthetic climate’ from monthly average weather data. EMPG2 (European Modeling Group Program 2) is a modular program. It has the capability of handling a wide verity of transient thermal systems, system control strategies, and load types. Also, several programs for different solar heating processes have been developed. These programs were used as modules for TRNSYS modular program. For example, a simulation model for fresh water production

from a desalination system integrated in a greenhouse roof was developed by Chaibi [48]. This module was based on a set of heat balance equations including material layers and a brackish water layers. The equations were solved with the more general PC program, Engineering Equation Solver. For calculation of solar irradiation, the simulation code TRNSYS was used. A preliminary study of a solar-heated low temperature space heating system with seasonal storage in the ground was performed [49]. The system performance was evaluated using simulation module (DST) [50] for duct ground heat storage model. DST program was used as a module for the modular program TRNSYS.

The following are the advantages of sequential modular approach [51]: on the module level, one or more specialized algorithms can be used with each module to solve the model equations thus the module calculations can be very efficient and robust. The engineer easily understands the sequential modular programs, because the information flow in the program closely resembles the material flow in the process. Also, the information flow structure makes error checking fairly easy.

The disadvantages are [6]

- The sophisticated handling of design specifications.
- The presence of multiple nested iteration loops.
- Not well suited to process optimization.

The handling of design specifications, typically equations of the form $x=$constant, by introducing additional iteration loops is obviously an inefficient way to handle such simple equations. The second problem can be explained by noting that the accelerated subroutine loops used to converge the tear stream, together with any control loops used to handle design specifications, may represent the outmost loops in a hierarchy of nested iteration loops. Within these loops are many iteration loops that may be needed within the process unit modules, and at the innermost level any loops that may exist within the physical property subroutines called by the unit modules. Problems involving large systems of nested iteration loops would be very expensive and time-consuming to solve. Finally, the optimization problem cannot be handled easily by the sequential modular approach, because adding more outer iteration loop for optimization will complicate the numerical solution.

Because of the fundamental problems described above, there has been recent interest in an alternative approach to process simulation and optimization. This approach namely the simultaneous modular approach is discussed below.

3.2.2. Simultaneous modular approach

In the case of the simultaneous modular approach, the simulation problem is seen as being one of solving a large set of linear and non-linear equations. The modules present the executive with the equations describing the unit process. The executive assembles all these equations and chooses the optimum method of solution for the whole system. The QUASILIN equation-oriented flow sheeting program was described by Hutchison et al. [52]. Its performance on several simulation, design, and optimization problems was reported. Newton's method was used for equation solving and the Powell successive quadratic programming algorithm for optimization.

Though the simultaneous approach is commonly used in chemical and thermal processes simulation, not many studies for solar heating process simulation using this technique have been published so far.

On one hand this approach provides flexibility in handling design constraints and it has advantages in problems with recycle structure [1,45,53]. Perhaps the most important benefits of this approach arise when performing optimization performance calculations or dynamic simulation. Here the ability to solve repeatedly and quickly a large set of non-linear algebraic equations are useful.

On the other hand, the disadvantages are [54] great effort required in the development of an intelligent program for coordination. A universal numerical procedure, which cannot be adapted to the structural properties of the individual blocks, is needed.

3.3. Structure of a simulator

From the early stage of having special purpose (one-off) program for simulating one process or one unit, the art of solar heating process simulation has developed into an advanced form, where proficient programs can simulate a large number of processes and configurations.

The main components of a simulation package are shown in Fig. 3. The package can be a fixed structure or a flexible structure. Programs with rigid structure are simple and straightforward. All the user has to supply, is the data, and the executive handles the program in the same way, irrespective of the sort of the process simulated. Unfortunately, all unit modules have to be loaded into the computer main memory whether or not many of the routines are relevant for the process being simulated. As these programs grow to include more unit modules, physical, and thermodynamic property calculations and wider output options, the complexity increases.

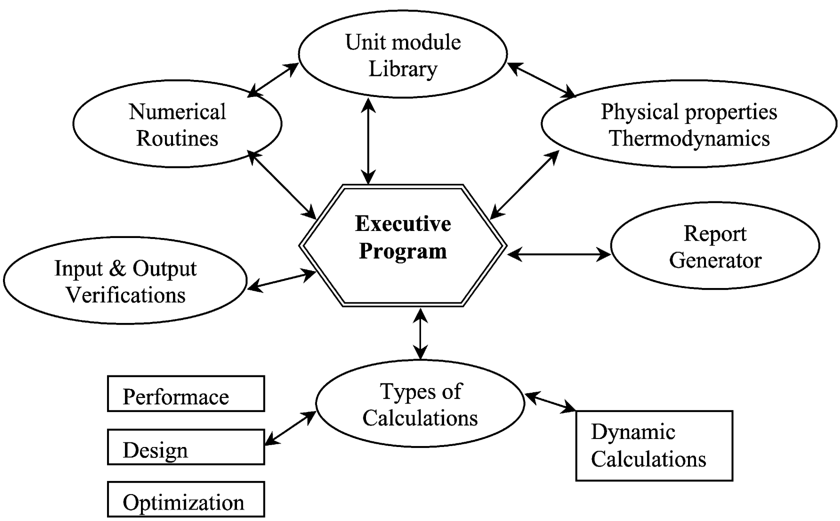

Fig. 3. Structure of a modular program.

Fortunately, most modern simulators use a flexible or variable structure. In the flexible structure, a problem-oriented language (POL) is used. The process topology can be explained by sentences. Only those modules that are actually needed are loaded. Data storage space may be allocated only as required by the size of the problem. The variable structure simulator provides greater flexibility and modularity. From Fig. 3, it is seen that the structure of a simulator essentially consists of five phases:

- input and input verification
- calculation
- processing
- output

The input should consist of process topology, information on all input streams, design parameters. Process topology is defined through POL. Feed stream information consists of flow rate, composition, temperature, and pressure. The design parameters of the units may be solar collector area, heat exchanger area, etc. Convergence criteria would normally be the tolerance on the convergence of recycles calculations. The maximum number of iterations allowed may also be specified.

The processing stage consists of generating the main program in a procedure-oriented language, compiling the program, loading all the required modules for the simulation, linking the main program and all subprograms, and allocated storage prior to the execution. Most simulators have extensive input data checking facilities as part of the processing phase.

The calculation stage requires unit module algorithms or equation sets, physical properties data, thermodynamic property estimation routines, numerical methods for convergence promotion and any user-supplied algorithms. In almost all simulators, a stream table is a common feature of output. The table consists of stream flow rate, composition, temperature, pressure, and enthalpy for all streams in the process. The post-processing phase would generally constitute cost estimation and economic analysis.

4. Numerical techniques

Computer solutions of individual solar heating process units are often highly iterative [3]. Often the models of these units involving rather sophisticated numerical methods for rapid convergence [55]. By connecting these individual units to form entire process, one or more recycle streams may be involved. When this situation exists, it often becomes very difficult to obtain a numerical solution. If more than one recycle loop is present, the problem tends to grow exponentially. It is also possible that the particular process is computationally unstable, meaning that a solution cannot be obtained by conventional techniques. Cavett [56] has analyzed the problems of simulated processes involving recycle loops in terms of existing numerical mathematics and attempts to apply more sophisticated techniques to their solution. Several methods are considered, including successive substitution, relaxation, and Newton's method.

Generally, solar heating process simulation gives rise to the need for solving sets of linear and non-linear algebraic equations. For steady-state calculations, the equations are naturally algebraic, while dynamic problems involving mixed systems have algebraic and differential equations whose solution in turn involves iterative solution of algebraic systems. This problem is most effectively dealt with by either Newton's Raphson (NR) method or a quasi-Newton method. However, NR method is usually a slower method than a specially tailored numerical scheme for solving the equations describing a particular unit. A wide variety of iterative solution procedures for solving linear and non-linear equations are adopted for solving solar heating processes [3].

5. Program evaluation (numerical results validity)

The question considered in this section is simple, but fundamental. How do we know that the results obtained numerically are correct?

To build confidence in large-scale computer programs for solar heating systems simulation, the programs must be reliable, free of bugs, and a large number of different problems must be solved by it. In assessing the reliability of the final results, the accuracy and precision should be considered [43]. Accuracy may be expressed as how closely the experimental results agree with the true or most probable values. In contrast, precision may be defined as how closely a set of measurements of the same quantity agrees with each other. Thus, accuracy expresses the correctness of the measurement whereas precision describes the predictability of the measurements.

The validation activity basically differs from classical comparisons between experimental data and theoretically predicted values, because it accounts not only for the measuring errors to be assigned to the experimental data, but also for the uncertainty to be associated with the calculated values as a result of errors on measured input data and the uncertainty about the correct value of the various parameters describing the process. Experimental evaluation for some of the published mathematical models for water desalination by solar still was presented by Abd El Kader et al. [25]. The validity and applicability of these models under real operating conditions were examined.

6. Future development

The availability of inexpensive, yet powerful personal computers has now opened new applications for the development of programs adapted to these personal computers. One of the essential aspects for the development of software for personal computers is user friendliness. In other words, the user must be in a position to enter the process topology and data interactively. Also, the user must be able to modify/change any solar heating process unit with minimum effort and maximum efficiency and flexibility. This can be achieved by using graphical user interface. This approach is a strong move from the representation of a system and its performance as simple lists of numbers and letters, the characteristics of the most present programs, to graphical representations that can be achieved by graphical interface.

The use of exergy analysis for rating and optimizing the performance of energy conversion systems is accepted on a worldwide basis as one of the most reliable tool available for this purpose [5,57]. Using this analysis, many solar heating system units have been developed [59–61]. However, the exergy concept has not yet been used in a general modular program. By considering the entropy generation as well as the material and energy balances equations a realistic model can be obtained. Each individual component or assembly can then be optimized, by minimizing the respective entropy generation.

7. Summary

It is evident from the foregoing discussion that simulation is a very important tool for performance, design, and optimization of solar heating systems. These systems which are governed by the principles of heat transfer, thermodynamics, fluid mechanics, and mass transfer, arise in a wide range of solar engineering applications. The mathematical models representing these applications may comprise a large system of equations caramelized by complexity, non-linearity, and implicitly. Many computer programs for different solar heating processes are reported. These programs are classified in this work into two types. First, special purpose programs (one-off programs) and second, general-purpose programs (or modular programs). Various aspects of these programs such as the structure, computational technique, advantages, and disadvantages of these programs are illustrated. The basic considerations involved in numerical modeling, particularly those concerned with accuracy and validation, are discussed.

The thermal engineer involved with process simulation is working in a very dynamic environment. Two points for future development are pointed. They are using the exergy concept in modeling a general modular program, and using the new feature of the visual programming in building flexible, and easy to manage, programs with comfortable interface.

References

[1] Rosen EM. Steady state chemical process simulation: a state of the art review. In: Squires RG, Reklsfitis GV, editors. Computer applications to chemical engineering. ACS Symposium Series, vol. 124, 1980. p. 3.

[2] Boehm R. Introduction and trends in the thermal design field. In: Boehm R, editor. Developments in the design of thermal systems. Cambridge: Cambridge University Press; 1977.

[3] Elsayed MM, Taha IS, Sabbagh JA. Design of solar thermal systems. Jeddah, Saudi Arabia: Scientific publishing center, King Abdulaziz University; 1994.

[4] Duffie JA, Beckman WA. Solar engineering of thermal Processes, 2nd ed. New York: Wiley; 1991.

[5] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: Wiley; 1996.

[6] Chen H, Stdtherr MA. A simultaneous modular approach to process flow sheeting and optimization. AlChE J 1985;31(11):1843–55.

[7] O'Dell MP, Mitchell JW, Beckman WA. Design method and performance of heat pumps with refrigerant-filled solar collectors. ASME J Solar Energy Eng 1984;106:159–64.

[8] Walker HA, Davidson JH. Analysis and simulation of a two-phase self-pumping water heater. ASME J Solar Energy Eng 1990;112:153–60.

[9] Sokolov M, Arbel A. Freshwater floating collector—type solar pond. Solar Energy 1990;44(1).
[10] El-Nashar AM. Computer simulation of the performance of a solar desalination plant. Solar energy 1990; 44(4).
[11] Nguyen CT, Galanis N. Prediction of long-term performance of active solar heating systems using daily hours of bright sunshine. ASME J Solar Energy Eng 1984;106:322–6.
[12] Shafeev AI. Modeling of solar heating systems for an individual house. Geliotekhnika 1991;27(2):55–9.
[13] Shafeev AI. Numerical simulation of active air systems for solar heat supply of an individual house. Appl Solar Energy 1993;29(6).
[14] Norton B, Probert SD. Diurnal performance of themosyphonic solar water heaters—an empirical prediction method. Solar Energy 1987;39(3):257–65.
[15] Chirarattananon S, Chinporncharoenpong C, Chirarattananon R. A steady-state model for the forced convection solar cabinet dryer. Solar Energy 1988;41(4):349–60.
[16] Ibrahim AO, Khalifa MA. Computer simulation of the solar pressure cooker. Solar Energy 1988;40(3): 259–68.
[17] Svard CD, Mitchell JW, Backman WA. Design procedure and application of solar-assisted series heat pump systems. ASME J Solar Energy Eng 1981;103:135–43.
[18] Sudhakar K, Krishna MM, Rao DP, Soin RS. Analysis and simulation of a solar water pump for lift irrigation. Solar Energy 1980;24:71–82.
[19] Jesch LF, Braun JE. Variable volume storage and stratified storage for improved water heater performance. Solar Energy 1984;33(1):83–7.
[20] Kaushik S, Sheridan N, Lam K, Kaul S. Dynamic simulation of an ammonia–water absorption cycle solar heat pump with integral refrigeration storage. Heat Recovery Syst 1985;5(2):101–16.
[21] Klemens S, Vieira ME, Faber C, Muller C. Solar thermal desalination system with heat recovery. Desalination 2001;137:23–9.
[22] Bojic B, Kalogirou S, Petronijevic K. Simulation of a solar domestic water heating systems using a time marching model. Renewable Energy 2002;27:441–52.
[23] Dai YJ, Wang RZ, Zhang HF. Parametric analysis to improve the performance of a solar desalination unit with humidification and dehumidification. Desalination 2002;142:107–18.
[24] Nafey AS, Fath H, El-Helaby Soliman A. Solar desalination using humidification dehumidification processes. Part I. A numerical investigation. Energy Convers Mgmt 2004;45:1243–61.
[25] El Kader A, Nafey AS, Elmotalip A, Mabrouk A. Experimental evaluation of still mathematical models Fourth International Water Technology Conference, Alexandria, Egypt 1999 p. 197–205.
[26] Robert PG, Robert BS. Flexible method for the solution of distillation design problems using the Newton–Raphson technique. Ind Eng Chem Process Des Dev 1970;9(1):78–84.
[27] John FT. A new simulation method for equilibrium stage processes. AICHE J 1970;16(2):229–32.
[28] Lucia A, Macchietto S. New approach to approximation of quantities involving physical properties derivatives in equation-oriented process design. AlChE J 1983;29(5):705–12.
[29] Hlavacek V, Rompay P. Simulation of countercurrent separation processes via global approach. Comput Chem Eng 1985;9(4):343–50.
[30] Dakhoul YM, Somers RE, Haynes RD. A conceptual design for a space-based solar water. Solar Energy 1990;44(3).
[31] Adhikari RS, Ashvini Kumar, Sootha GD. Simulation studies on a multistage stacked tray solar still. Solar Energy 1995;54(5).
[32] Huang BJ, Hsieh CT. A simulation method for solar thermosyphon collector. Solar Energy 1985;35(1).
[33] Selcuk K. Thermal and economic analysis of the overlapped-glass plate solar air heater. Solar Energy 1971; 13.
[34] Kenna JP. The multiple layer solar collector. Solar Energy 1983;30(3).
[35] Ghoneim AA. Comparison of theoretical models of phase-change and sensible heat storage for air and water-based solar heating system. Solar Energy 1989;42(3).
[36] Zhao Q, Sadler GW, Leorard JJ. Transient simulation of flat-plate solar collectors. Solar Energy 1988;40(2): 167–74.
[37] Choudhury C, Garg HP. Evaluation of a jet plate solar air heater. Solar Energy 1991;46(4).

[38] El-Nashar AM, Qambiyeh AA. Performance simulation of the heat accumulator of the Abu-Dhabi solar desalination plant. Solar Energy 1990;44(4).
[39] Johannsen A. Performance simulation of regenerating type solar collectors. Solar Energy 1983;30(2):87–92.
[40] Fath HES, Ghazy A. Solar desalination using humidification–dehumidification technology Fifth International Water Technology Conference IWTC, Alexandria, Egypt 2000.
[41] Mousa A, Yousef Z, Helal A, Saif A. Modeling and performance analysis of a solar desalination unit with double glass cover cooling. Desalination 2002;143:173–82.
[42] AL-Kharabsheh S, Yogi GD. Analysis of an innovative water desalination system using low-grade solar heat. Desalination 2003;156:323–32.
[43] Hlavacek V. Analysis of a complex plant-steady state and transient behavior. Comput Chem Eng 1977;1: 75–100.
[44] Evans LB. Advances in process flow sheeting systems. In: Mah RSH, Seider WD, editors. Foundations of computer-aided chemical process designed, vol. 1. New York: American Institute of Chemical Engineers; 1980. p. 425–69.
[45] Westerberg AW, Hutchison HP, Motard PL, Winter P. Process flow sheeting. Cambridge: Cambridge University Press; 1979.
[46] Wells GL, Robson PM. Computation for process engineers.: Billing and Sons Limited; 1973.
[47] Young SK. Integrated solar energy systems optimization. ASME J Solar Energy Eng 1982;104:310–6.
[48] Chaibi MT. Analysis by simulation of a solar still integrated in a greenhouse roof. Desalination 2000;128: 123–38.
[49] Nordell B, Goran H. High temperature solar heating seasonal storage system for low temperature heating of buildings. Solar Energy 2000;69:511–23.
[50] Hellstrom G, Sanner, B. EED-earth energy designer. Version 1.0, User's manual. Prof. Dr Knoblich and Partner Gmbh, Virchowstrasse 4, D-35578 Wetzlar, Germany; 1997.
[51] Jaluria Y. Design and optimization of thermal systems. New York: McGraw-Hill; 1998.
[52] Hutchison HP, Jackson DJ, Mortion W. The development of an equation-oriented flowsheet simulation and optimization package. I. The QUASILIN program. Comput Chem Eng 1986;10(1):19–29.
[53] Shacham M, Macchietto S, Stutzman LF, Babcock P. Equation oriented approach to process flowsheeting. Comput Chem Eng 1982;6:79.
[54] Umeda T, Nishio M. Comparison between sequential and simultaneous approaches in process simulation. Ind Eng Chem Process Des Dev 1972;11(2).
[55] Shacham M. Computing software for the solution of systems of nonlinear algebraic equations arising n chemical engineering. Comput Chem Eng 1985;9(2):103–12.
[56] Cavett RH. Application of numerical methods to the convergence of simulated processes involving recycle loops Paper presented to American Petroleum Institute, Division of Refining, Philadelphia, Pennsylvania, USA, vol. 34 1963 p. 57–76.
[57] Ahern JE. The exergy method of energy systems analysis. New York: Wiley/Interscience; 1980.
[58] Suzuki A. A fundamental equation for exergy balance on solar collectors. ASME J Solar Energy Eng 1988; 110:102–6.
[59] Manfrida G. The choice of an optimal working point for solar collectors. Solar Energy 1985;34(6):513–5.
[60] Said SAM, Zubair SM. On second-law efficiency of solar collectors. SME J Solar Energy Eng 1993;115: 2–4.
[61] Rosen MA, Hooper FC, Barbaris LN. Exergy analysis for the evaluation of the performance of closed thermal energy storage systems. ASME J Solar Energy Eng 1988;110:255–61.